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DISCLAIMER

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Summary

This paper describes the design and analysis of the TMX Upgade Vacuum System. TMX Upgrade[1] is a modification of the TMX tandem mirror device[2]. It will employ thermal barriers to further improve plasma confinement. Thermal barriers are produced by microwave heating and neutral-beam pumping. They increase the feasibility of tandem-mirror reactors by reducing both the required magnetic field strengths and the neutral-beam injection voltages.

A cutaway drawing of TMX-Upgrade is shown in Fig. 1. The neutral beams introduce hydrogen gas that must be pumped to maintain low pressures near the plasma surface. Concentric cylinders, cooled by liquid nitrogen, divide the vacuum system into different regions. As indicated in Fig. 2, these are the first injector region, the second injector region, and the plasma region. The walls dividing the second injector and plasma regions are not shown in Fig. 1.

The TMX-Upgrade integrates the neutral-beamline design and the machine design to simplify construction and allow greater experimental flexibility. The design goal was to maintain operating vacuum pressures below 5×10^{-7} Torr.

The vacuum requirements for TMX-Upgrade are more stringent than for the earlier TMX device for a number of reasons. The longer plasma duration requires that the hydrogen gas be pumped for a longer time. The larger plasma size, fueled with the same neutral-beam current, requires that the gas be pumped better. In addition, the plasma parameters are projected to be improved. The expected longer central-cell ion confinement time and the higher temperatures require charge-exchange losses and electron cooling to be correspondingly reduced. Poor vacuum conditions reduce plasma parameters or raise the required neutral-beam and microwave heating powers. Thirdly, the TMX-Upgrade end cells operate at lower plasma density to allow the 28-GHz microwave power to penetrate. The lower density allows neutral gas to penetrate the plasma more readily and to remove hot end-cell ions by charge exchange.

In this paper we describe how the system pumps thermal gas from the neutral beams. Other papers describe in more detail the mechanical design,[3] first wall design and analysis,[4] and operating procedures.[5]

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Vacuum System Walls

The vacuum-system wall material is titanium, freshly gettered preceding each shot. Titanium is evaporated from 270 m of 3 mm wire before each shot depositing an average of about 10 monolayers of titanium on 670 m^2 of wall area. All the TMX Upgrade magnets are located within the vacuum system. To mitigate the effects of magnet leaks they can be differentially pumped. In addition, first walls hide the magnets from direct view of the plasma.

Gas Sources

The main source of gas is hydrogen from the neutral beams. To reduce this input below previous TMX operation, we have tested beam performance at lower gas input. Measurements indicate we can operate beams with 20 $\text{Torr}\cdot\ell\cdot\text{s}^{-1}$, divided as indicated in Table 1. The largest gas source is thermal gas into the first region. It sets the required surface of the first injector region. The gas reaches the plasma region either by diffusion from the preceding region or by free streaming (direct line-of-sight flow from the beam neutralizers). The free-streaming gas component was estimated from neutral-beam aperture sizes connecting various regions.

Energetic sources of gas include unneutralized beam ions, beam impingement on apertures and dumps, plasma charge exchange products, and end-wall flux. For this 75-ms-pulsed experiment, a vanadium foil is a suitable beam dump. Gas release from such a dump and sources from other energetic species are estimated in Ref. 4.

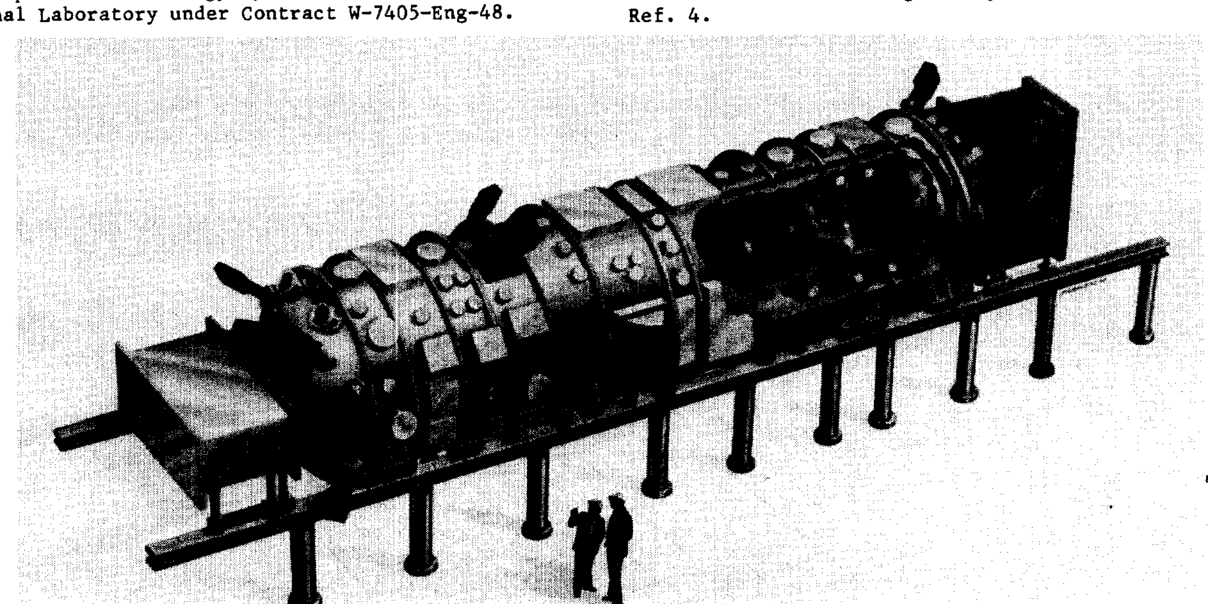

Fig. 1. The TMX Upgrade vacuum system. The outside diameter is 4 m and the overall length is 21 m.

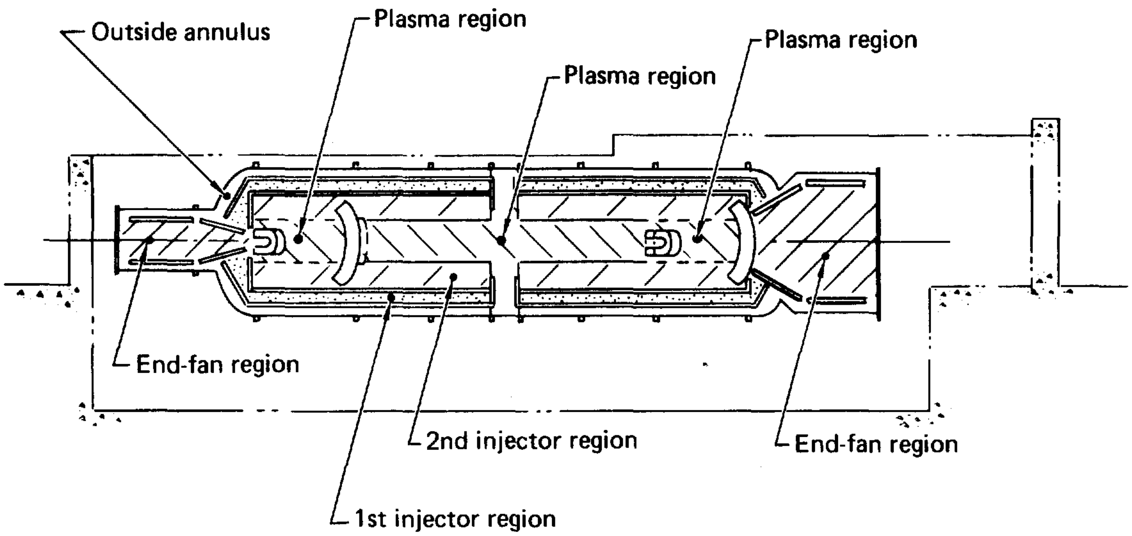

Fig. 2. Schematic drawing showing the different regions of the TMX-Upgrade vacuum system.

Table 1. Neutral beam gas distribution.

Component	Quantity (Torr•ℓ•s^{-1})
Energetic neutrals	3.6[a]
Ions	1.8[a]
Free streaming to plasma region	0.1
Free streaming to second region	0.25
Input to first region	14.25
Total	20.0

[a]We used 11.3 atom equivalent amperes equal to 1 Torr•ℓ•s^{-1}.

Gas fueling is another gas source. Expected fueling rates range from 4 to 400 Torr•ℓ•s^{-1}. Central-cell particles are replaced by gas introduced between two limiters, called a gas box. The gas boxes are located in the central cell near the end-cell mirrors where the plasma cross section is highly elliptical (5 cm x 60 cm). Gas penetrates the 2.5-cm distance to the axis to refuel the central cell. To control the density buildup rate, the gas feed is electrically programmable.

Analysis of the Vacuum System

The model for the TMX-Upgrade vacuum system, shown in Fig. 3, was employed to evaluate its performance for pumping thermal gas. A summary of the vacuum system pumping speeds, conductances, and gas sources are given in Tables 2 through 4. The vacuum pressures in each region have been calculated as a function of time. Steady state is achieved after about 30 ms. Equilibrium pressures can be estimated quite accurately as outlined here and summarized in Table 5. We do not calculate here effects of gas from energetic particle reflux or gas ionization at the plasma edge.

Table 3. Summary of conductances connecting vacuum regions.

Purpose	1st to 2nd injectors (one half)	2nd to end cell	2nd to central cell
Beams in (m^2)	0.38	0.36	0.24
Beams out (m^2)	2.60	0.32	0.32
Getter leads (m^2)	0.41	0.0	0.0
ECRH (m^2)	0.08	0.08	0.0
Diagnostics (m^2)	0.65	0.65	0.0[a]
Miscellaneous (m^2)	0.20	0.10	0.20
Total (m^2)	4.22	1.51	0.76
Conductance (10^5 ℓ•s^{-1})	9.6	3.4	1.7

[a]Diagnostics are through the short midplane section shown in Fig. 1 which is connected directly to the plasma region.

Table 2. TMX Upgrade vacuum system characteristics.

	Volume (m^3)	Surface area (m^2) Cold[a]	Surface area (m^2) Warm[b]	Pumping speed (10^6 ℓ•s^{-1}) Titanium	Pumping speed (10^6 ℓ•s^{-1}) Plasma
1st injector (half)	47	175	-	16	-
2nd injector (half)	40	70	30	10	-
Plug (each)	4.6	-	7.7	0.1	2.2[c]
Central cell (full)	20	-	32	0.4	3.7[d]
End fan (each)	11	25	3	1.3	-
Total (both ends)	225	540	113	55	8

[a]Sticking coefficient at 80K = 0.40

[b]Sticking coefficient at 300 to 400K = 0.03

[c]Sticking coefficient = 0.91

[d]Sticking coefficient = 0.85

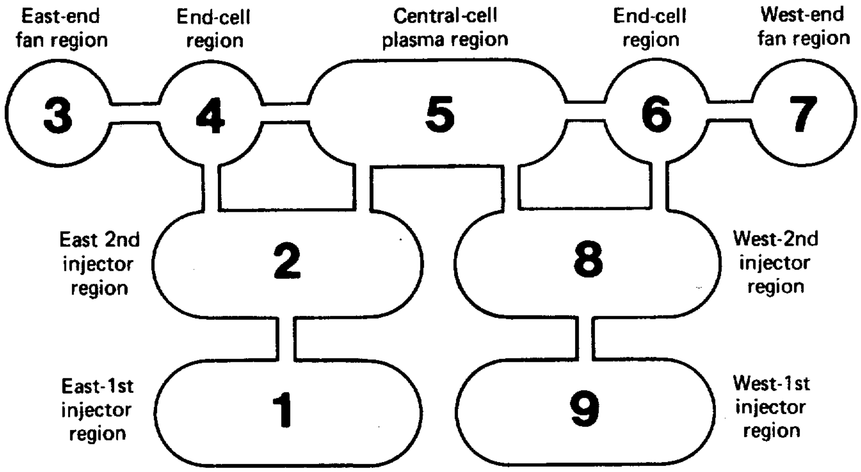

Fig. 3. Model used to analyze TMX-Upgrade performance for pumping thermal gas.

Table 4. Sources of thermal gas.

	Each end cell	Central cell
Diffusion ($Torr \cdot \ell \cdot s^{-1}$)	0.44	0.22
Free streaming ($Torr \cdot \ell \cdot s^{-1}$)	0.72[a]	0.6[b]
Total ($Torr \cdot \ell \cdot s^{-1}$)	1.16	0.53
Pumping speed ($\ell \cdot s^{-1}$) (including plasma)	2.3×10^6	3.7×10^6
Equilibrium pressure (Torr)	5.0×10^{-7}	2.0×10^{-7}

[a]Assumes nine 8 x 40 cm apertures 1 m from end-cell midplane.
[b]Assumes six 8 x 40 cm apertures 0.5 m from machine axis.

The surface area of the first injector region was calculated based on one half a monolayer coverage from 24 neutral beams each introducing 14.2 $Torr \cdot \ell \cdot s^{-1}$ (see Table 1) of hydrogen for 75 ms,

$$\text{Area} = \frac{14.2\ Torr \cdot \ell \cdot s^{-1} \times 24\ \text{beams} \times 0.075\ s}{2.5 \times 10^{18}\ \text{molecules}/m^2} \times \frac{3.5 \times 10^{19}\ \text{molecules}}{Torr \cdot \ell \cdot s^{-1}} = 350\ m^2$$

In TMX Upgrade, this surface is titanium gettered on liquid-nitrogen-cooled panels. The two ends are separated by a short section at the central-cell midplane. For an average sticking coefficient of 0.4, this results in a pumping speed of $1.6 \times 10^7\ \ell \cdot s^{-1}$ in each end. During steady state, the expected pressure in the first region will be 14.2 $Torr \cdot \ell \cdot s^{-1}$ x 12 beams/1.6 x $10^7\ \ell \cdot s^{-1} = 10^{-5}$ Torr.

The gas (at 80K) will flow to the second injector region through beam and diagnostic apertures (8.4 m^2 total). From the resulting conductance, we estimate the gas input to the second region to be $Q_2 = 10^{-5}$ Torr x $9.6 \times 10^5\ \ell \cdot s^{-1} = 9.6\ Torr \cdot \ell \cdot s^{-1}$.

Free-streaming gas input from the neutral beams is 0.25 $Torr \cdot \ell \cdot s^{-1}$ x 12 beams = 3 $Torr \cdot \ell \cdot s^{-1}$. The second region pumping speed is $2.0 \times 10^7\ \ell \cdot s^{-1}$. The pressure is then expected to be $(9.6 + 3\ Torr \cdot \ell \cdot s^{-1})/(1.0 \times 10^7\ \ell \cdot s^{-1}) = 1.3 \times 10^{-6}$ Torr. Thus the pressure in the second region is an order of magnitude lower than that in the first.

The thermal gas sources to each end cell are from the second injector region (1.5 m^2 total aperture implies 1.3×10^{-6} Torr x $3.4 \times 10^5\ \ell \cdot s^{-1}$ = 0.44 $Torr \cdot \ell \cdot s^{-1}$) and from free streaming gas

Table 5. Equilibrium pressures due to thermal hydrogen from the neutral-beam injectors.

Region	Pressure (Torr)
First injector	1.0×10^{-5}
Second injector	1.3×10^{-6}
End cell	5.0×10^{-7}
Central cell	2.0×10^{-7}

(0.08 $Torr \cdot \ell \cdot s^{-1}$ x 9 beams = 0.72 $Torr \cdot \ell \cdot s^{-1}$). The end-cell pumping speed is $2.3 \times 10^6\ \ell \cdot s^{-1}$, mainly by the plasma. The end cell pressure is thus $(0.44 + 0.72\ Torr \cdot \ell \cdot s^{-1})/2.3 \times 10^6 = 5.0 \times 10^{-7}$ Torr.

The thermal-gas sources to the central cell are from the second region (13×10^{-6} Torr x $1.7 \times 10^5\ \ell \cdot s^{-1}$ = 0.22 $Torr \cdot \ell \cdot s^{-1}$) and from free streaming (0.1 $Torr \cdot \ell \cdot s^{-1}$ x 6 beams = 0.6 $Torr \cdot \ell \cdot s^{-1}$). The central-cell pumping speed is $4.1 \times 10^6\ \ell \cdot s^{-1}$. The steady state central cell pressure is then $(0.22 + 0.6\ Torr \cdot \ell \cdot s^{-1})/4.1 \times 10^6\ \ell \cdot s^{-1} = 2.0 \times 10^{-7}$ Torr.

Conclusions

We have described the TMX-Upgrade vacuum system design. Gettering on 540 m^2 of liquid nitrogen cooled liners will be used to pump the neutral-beam gas at a pumping speed of $5.5 \times 10^7\ \ell \cdot s^{-1}$. Thermal gas from the neutral beams results in equilibrium pressure of 5×10^{-7} Torr in the end cells and 2×10^{-7} Torr in the central cell, meeting our design goal.

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